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Spontaneous Currents in Superconducting Systems with Strong Spin-Orbit Coupling

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We show that Rashba spin orbit coupling at the interface between a superconductor and a ferromagnet should produce a spontaneous current in the atomic thickness region near the interface. This current is counterbalanced by the superconducting screening current flowing in the region of the width of the London penetration depth near the interface. Such a current carrying state creates a magnetic field near the superconductor surface, generates a stray magnetic field outside the sample edges, changes the slope of the temperature dependence of the critical field H_{c3}, and may generate the spontaneous Abrikosov vortices near the interface.

The influence of strong spin-orbit coupling (SOC) on superconducting systems has stayed in the focus of intensive research for more than two decades (see as reviews Refs. [1,2]). In the absence of inversion symmetry an electron spin $\vec{\sigma}$ becomes coupled with the orientation of the momentum $\vec{p}$, which produces the nontrivial "helicity" of the electronic energy bands. The resulting helical states [3,4] play the central role in the appearance of Majorana modes [5], the formation of Josephson φ_0 junctions with spontaneous phase difference in the ground state [6–9], and the emerging of different types of superconducting phases with finite Cooper-pair momentum which are similar to the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) states [2].

One of the key questions related to the physics of superconducting systems with broken inversion symmetry is the existence of the spontaneous electric current originating from the interplay between SOC and magnetic order. Indeed, the SOC of the Rashba type in noncentrosymmetric metals provides the additional contribution $\propto (\vec{\sigma} \times \vec{p}) \cdot \vec{n}$ to the electron energy ($\vec{n}$ is the unit vector along the axis with broken inversion symmetry). The ferromagnetic order or strong external magnetic field polarizes the electron spins, making the momentum direction along the vector $\vec{\sigma} \times \vec{n}$ energetically more favorable compared with others, which suggests the possibility of having a spontaneous electric current.

A detailed analysis shows that the situation is more subtle and typically no spontaneous current appears. In bulk materials the appearance of the current-carrying states is unfavorable because of the large corresponding kinetic energy of the condensate. For two-dimensional superconductors the SOC induces several types of FFLO-like helical phases with nonzero Cooper-pair momentum $\vec{p}$ in the ground state [10–14]. It was claimed that in the presence of the in-plane magnetic field such states can carry the supercurrent [15]. However, an accurate analysis shows that in all mentioned situations the Cooper-pair wave function $\psi \propto e^{i\vec{p}\vec{r}}$ does not produce an electric current since the SOC modifies the quantum mechanical expression for the current by adding the terms which exactly compensate the usual orbital contribution [4,16]. Note that it has been predicted that in the unconventional d-wave and chiral p-wave superconductors or at the interfaces between the s-wave superconductors and half-metals the appearance of the Andreev edge states may lead to the ground state with broken time-reversal symmetry [17–27]. The transition to these states typically occurs well below T_c and may be accompanied by spontaneous current generation.

In this Letter we demonstrate that local Rashba SOC produces the spontaneous currents flowing along the surface of the bulk s-wave superconductors, provided this surface is put in contact with a layer of a ferromagnetic insulator. In contrast with the surface magnetism in unconventional superconductors, in our case the spontaneous currents appear at the superconducting transition. Remarkably, the emergence of such current does not require the presence of the external magnetic field and is controlled by the exchange field inside the ferromagnet and the strength of the SOC. Experimentally the spontaneous current is shown to be revealed through the appearance of the magnetic field near the interface, which can be detected in the local probe measurements, and also changes the behavior of the critical field H_{c3} with variations of temperature T. Specifically, the slope of the dependence $H_{c3}(T)$ becomes dependent on the relative orientation between the external magnetic field and the exchange field in the ferromagnet. The spontaneous current can also serve as a probe of SOC, and we may expect that the appropriate conditions to observe this effect should be realized at the interface of ferromagnetic insulator and a superconductor with large nuclear charge Z, like Pb or Hg. Note that recently the unusual enhancement of superconductivity by a parallel magnetic field was observed in thin Pb film [28]. Following the authors of Ref. [28], the most probable

mechanism of this phenomenon is related to a large SOC in Pb.

To describe the physics of these phenomena, we use the Ginzburg-Landau (GL) model, which is relevant at temperatures T close to the superconducting transition temperature T_c. In the presence of Rashba SOC the density $f(\mathbf{r})$ of the GL free energy $F = \int f(\mathbf{r}) d^3\mathbf{r}$ reads [12,13] (we use the system of units where $\hbar = c = 1$)

$$f(\mathbf{r}) = a|\psi|^2 + \gamma|\hat{\mathbf{D}}\psi|^2 + \frac{b}{2}|\psi|^4 + \frac{(\mathrm{rot}\mathbf{A})^2}{8\pi} + (\vec{n} \times \vec{h}) \cdot [\psi^* \varepsilon(\mathbf{r}) \hat{\mathbf{D}}\psi + \mathrm{H.c.}]. \quad (1)$$

Here $a = -\alpha(T_c - T)$, b and $\gamma > 0$ are the standard GL coefficients, $\psi = |\psi| e^{i\varphi}$ is the superconducting order parameter with $|\psi|^2 = |a|/b$, $\hat{\mathbf{D}} = -i\nabla + 2e\mathbf{A}$ is the gauge-invariant momentum operator (here, $e > 0$), $\vec{n}$ is the unit vector in the direction along which the inversion symmetry is broken, $\vec{h}$ is the exchange field, and $\varepsilon(\mathbf{r})$ is the Rashba SOC constant, which is nonzero only inside the narrow region near the sample surface. We assume that h strongly exceeds the Zeeman splitting energy due to the external field, so that the renormalization of h in Eq. (1) due to magnetic field can be neglected.

The appearance of the spontaneous magnetic field is a generic phenomenon which is inherent for a wide class of S/F interfaces with SOC in different superconducting hybrids (see Fig. 1). We start from the simplest situation when a ferromagnetic (F) film is deposited on the surface of the half-infinite superconductor occupying the region $x > 0$ [Fig. 1(a)] so that the inversion symmetry is broken in the x direction and $\vec{n} = -\hat{\mathbf{x}}$. When the exchange field in the F layer has only the in-plane component $\vec{h} = h_z\hat{\mathbf{z}}$, the vector product $(\vec{n} \times \vec{h}) = h_z\hat{\mathbf{y}}$ is also parallel to the superconductor surface. We choose the external magnetic field $\mathbf{H}_0$ to be directed along the z axis: $\mathbf{H}_0 = H_{0z}\hat{\mathbf{z}}$. For simplicity, we do not account for the inverse proximity effect neglecting the spatial variations of $|\psi|$ in the S layer and also choose the gauge of the vector potential $\mathbf{A}$ in a way that $\nabla\varphi = 0$. This is justified in the case of the ferromagnetic insulator or, more generally, when the conductivity of the ferromagnet is much smaller than the normal state conductivity of the superconductor [29].

Assuming that the SOC is generated only inside the layer of the thickness l_{so} (we may expect that it is nm scale), which is much smaller than the coherence length $\xi = \sqrt{\gamma/|a|}$, we rewrite the last term in Eq. (1) as a surface contribution to the free energy,

$$F_{\mathrm{SO}} = 2|\psi|^2 \varepsilon l_{so} S(\vec{n} \times \vec{h}) \cdot (\nabla\varphi + 2e\mathbf{A})|_{x=0}, \quad (2)$$

where S is the area of the sample surface. The derivative of F_{SO} over $\mathbf{A}$ defines the surface supercurrent $\mathbf{J}$ originating from the SOC:

$$\mathbf{J} = -\frac{1}{S}\frac{\delta F_{\mathrm{SO}}}{\delta \mathbf{A}} = -\frac{1}{4\pi\lambda^2}\alpha_{so} h_z \hat{\mathbf{y}}, \quad (3)$$

where we introduce the SOC constant $\alpha_{so} = \varepsilon l_{so}/(2e\gamma)$ and the London penetration depth $\lambda = (32\pi e^2\gamma|\psi|^2)^{-1/2}$. Remarkably, the emergence of the spontaneous current $\mathbf{J}$ does not require the presence of the external magnetic field; it is a direct consequence of the interplay between the exchange field and the Rashba SOC.

The crucial difference between this result and the situation described in Ref. [16] is that in our case the field $\vec{h}$ has the exchange nature and does not depend on the vector potential. In contrast, when the Zeeman splitting of the energy bands for the spin-up and -down electrons is caused by the magnetic field $\mathbf{H} = \mathrm{rot}\mathbf{A}$, the expression for the surface current analogous to Eq. (3) contains an additional term coming from the derivative of $\mathbf{H}$ over $\mathbf{A}$, which exactly compensates the contribution Eq. (3) (see Ref. [16]).

According to the Maxwell equations the surface current $\mathbf{J}$ produces the magnetic field $\mathbf{H}$, which decays at the scale $\propto \sqrt{S}$. However, outside the superconductor this field

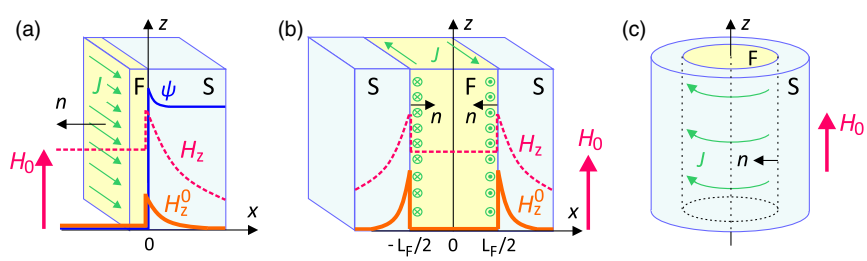

FIG. 1. Hybrid superconductor (S) ferromagnet (F) systems where the spin orbit coupling produces spontaneous currents. (a) S/F bilayer, (b) $S/F/S$ sandwich, and (c) bulk superconductor with the cylindrical ferromagnetic core. The direction of the spontaneous current $\mathbf{J}$ is shown with green arrows, the corresponding profile of the spontaneous magnetic field in the absence of external magnetic field is plotted schematically in orange, the distribution of the order parameter ψ is shown with the blue curve. The magenta curves show the magnetic field profiles in the presence of the external magnetic field $\mathbf{H}_0$ directed along the z axis. The unit vector $\mathbf{n}$ is the vector in the direction of the broken inversion symmetry at the S/F interfaces, which determines the energy of the spin orbit coupling.

should be compensated by the field induced by the screening Meissner current, so that

$$H_z(x) = \begin{cases} H_{0z} & \text{for } x < 0 \\ (H_{0z} + \Delta H)\exp(-x/\lambda) & \text{for } x > 0, \end{cases} \quad (4)$$

where $\Delta H = \alpha_{so} h_z/\lambda^2$ is the magnetic field step due to the surface current $\mathbf{J}$.

Note that the finite thickness $L_S \gg l_{so}$ of the S film does not substantially change the described phenomenon. In particular, if both surfaces of the superconductor are covered by the identical F layers with strong SOC, the magnetic field inside the S film (for $|x| < L_S/2$) reads $H_z(x) = (H_{0z} + \Delta H)\cosh(x/\lambda)\cosh^{1}(L_S/2\lambda)$, where the maximal value of H_z is determined by the SOC.

The spontaneous current gives rise to a slight variation of the order parameter near the sample surface. Indeed, taking the vector potential in the S layer in the form $A_y(x) = -\lambda\Delta H\exp(-x/\lambda)$, for $H_{0z} = 0$, one can check that the surface free energy due to SOC is $F_{\rm SO} = -\lambda S\Delta H^2/4\pi$. This energy gain is proportional to $|\psi|^3$, which makes the local increase of the order parameter favorable. To calculate $\psi(x)$ we assume that $\lambda \gg \xi$, and in the region where $|\psi|$ deviates from the equilibrium value $|a|/b$ the spatial variation of the magnetic field is negligibly small. The calculation shows [30]

$$\psi(x) = \psi_0\left(1 + \frac{3}{4}\frac{\lambda}{\xi}\frac{\Delta H^2}{H_{cm}^2}e^{\sqrt{2}x/\xi}\right), \quad (5)$$

where $H_{cm} = (2\sqrt{2}e\xi\lambda)^{1}$ is the thermodynamic critical field. Clearly, the obtained increase of the order parameter arises only at temperatures well below T_c, while at the transition temperature the effect vanishes. Note that the most favorable conditions for the growth of ψ are realized in the case of negligibly small inverse proximity effect.

In type-II superconductors the spontaneous surface currents substantially change the behavior of the critical magnetic field H_{c3}, which corresponds to the emergence of the localized superconducting states above the bulk upper critical field. The SOC and the exchange field in the F layer produce an additional current which interferes with the usual orbital one screening the external magnetic field and affects the conditions for the superconductivity nucleation. Detailed calculations in the spirit of Ref. [31] show that the dependence $H_{c3}(T)$ changes its slope near T_c, and for $H_{0z} > 0$, we find [30]

$$H_{c3}(T) \approx H_{c3}^0(T)(1 + \zeta\varepsilon h_z l_{so}/\gamma), \quad (6)$$

where $H_{c3}^0(T) = 1.6946(\alpha/2e\gamma)(T_c - T)$ is the standard dependence of the critical field in the absence of the SOC and $\zeta = 1.9847$. Remarkably, the sign of the deviation from $H_{c3}^0(T)$ is determined by the relative orientation of the magnetic field $\mathbf{H}_0$ and the exchange field $\mathbf{h}$ (see Fig. 2). Thus, despite the fact that the effect of the SOC is typically small, it can be observed experimentally by inverting the direction of the magnetic field.

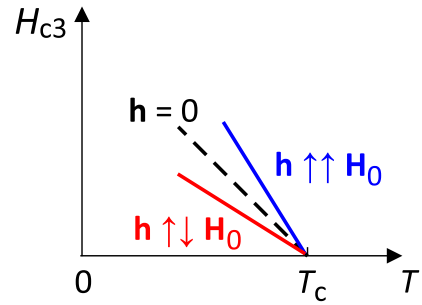

FIG. 2. The behavior of the critical field H_{c3} in the presence of the ferromagnetic layer with the spin orbit coupling in the case $\varepsilon > 0$. The red and blue curves correspond to the different relative orientation between the exchange field $\mathbf{h}$ and the external field $\mathbf{H}_0$, while the black dashed line shows the field H_{c3} in the absence of the F layer.

An even more interesting situation occurs when the F layer of the thickness L_F is placed between two bulk superconductors [see Fig. 1(b)]. Assuming that the SOC is nonzero only at the region of the thickness l_{so} near each S/F interface and $L_F \gg l_{so}$, one finds that inside the superconductors (for $|x| > L_F/2$) the magnetic field has the form $H_z(x) = (H_F + \Delta H)\exp[-(|x| - L_F/2)/\lambda]$, while inside the F layer (for $|x| < L_F/2$) the field intensity $H_z(x) = H_F$. Here the constant H_F should be defined from the minimization of the Gibbs free energy;

$$G = \int_{\infty}^{\infty}[H_z^2 + \lambda^2(\partial_x H_z)^2 - 2H_z H_{0z}]\frac{Sdx}{8\pi} + F_{\rm SO}, \quad (7)$$

where $F_{\rm SO} = -2\lambda S\Delta H(H_F + \Delta H)/4\pi$ (here we account for the fact that the spontaneous current appears at both S/F interfaces). Note that the magnetization $\mathbf{M}$ inside the F layer makes the difference between the magnetic intensity $\mathbf{H}$, which enters Eq. (7), and the magnetic induction $\mathbf{B} = \mathbf{H} + 4\pi\mathbf{M}$, which is nonzero even if $H_F = 0$. Performing the integration, we find

$$G(H_F) = G_1 + S(H_F^2 - 2H_F H_{0z})(L_F + 2\lambda)/8\pi, \quad (8)$$

where $G_1 = -(S\Delta H\lambda/4\pi)(\Delta H + 2H_{0z})$ does not depend on H_F. Interestingly, the minimum $G_{\min}$ of the function Eq. (8) corresponds to $H_F = H_{0z}$ and $G_{\min} = -(SL_F/8\pi)\times[H_{0z}^2 + (2\lambda/L_F)(H_{0z} + \Delta H)^2]$. This value is negative for any arbitrary H_{0z} and, thus, the state with spontaneous current is always favorable at $T < T_c$.

Finally, we consider the peculiar situation when the ferromagnetic cylinder of length L and radius $R \gg l_{so}$ is embedded into the bulk of the superconductor [see Fig. 1(c)]. In this case, the magnetic field profile is

$$H_z(r) = \begin{cases} H_F & \text{for } r < R \\ (H_F + \Delta H)\frac{K_0(r/\lambda)}{K_0(R/\lambda)} & \text{for } r \geq R. \end{cases} \quad (9)$$

Here K_0 is the modified Bessel function of the second kind and H_F is the constant corresponding to the minimum of the Gibbs free energy:

$$G = \frac{L}{4}\int_0^\infty [H_z^2 + \lambda^2(\partial_r H_z)^2 - 2H_z H_{0z}]rdr + F_{\rm SO}. \quad (10)$$

In Eq. (10) the SOC-induced surface free energy $F_{\rm SO}$ is determined by Eq. (2), where the vector potential $A_\theta|_{r=R} = -(H_F+\Delta H)RQ/2$, with $Q=2(\lambda/R)K_1(R/\lambda)[K_0(R/\lambda)]^{-1}$ has only an angular component. Substituting Eq. (9) into Eq. (10), we find

$$G(H_F) = G_2 + R^2L(H_F^2 - 2H_F H_{0z})(1+Q)/8, \quad (11)$$

where the value $G_2 = -(R^2L/8)(\Delta H^2 + 2\Delta H H_{0z})Q$ does not depend on H_F. Similar to the case of the $S/F/S$ system, the minimum of the function $G(H_F)$ formally corresponds to $H_F = H_{0z}$. However, in our doubly connected geometry the total magnetic flux $\Phi = \int_0^\infty B_z(r)2\pi rdr$ through the ferromagnetic cylinder and the adjacent superconducting layer of width $\sim\lambda$ is quantized, so that $\Phi = n\Phi_0$, where $\Phi_0 = \pi/e$ is the superconducting magnetic flux and n is an integer number. The magnetic induction $B_z(r)$ inside the F layer is $B_z(r) = H_z(r) + 4\pi M_z$, where M_z is the magnetization, which is assumed to be uniform. The corresponding values of the magnetic field inside the ferromagnet are

$$H_F^{(n)} = \left(\Delta H - 4\pi M_z + \frac{n\Phi_0}{\pi R^2}\right)\frac{1}{1+Q} - \Delta H. \quad (12)$$

The resulting dependence $H_F(H_{0z})$, which realizes the minimum of the Gibbs free energy Eq. (11), has the form of a staircase (see Fig. 3). The amplitude of the jumps $H_F^{(n+1)} - H_F^{(n)}$ does not depend on the parameters of the SOC and is determined by the radius of the F cylinder. In contrast, the position of these jumps is controlled by the SOC: the jump between the ground states with $H_F = H_F^{(n)}$ and $H_F = H_F^{(n+1)}$ occurs at the field $H_{0z}^{(n)} = [(\Phi_0/\pi R^2)\times(n+1/2) - 4\pi M_z - Q\Delta H]/(1+Q)$. This feature shows the way for the experimental determination of the value ΔH. Note that the steplike behavior of the field H_F is revealed at $R \sim \lambda$, while for $R \gg \lambda$ the distance between the steps is negligibly small and the dependence $H_F(H_{0z})$ becomes almost linear.

In summary, we predict the emergence of the spontaneous superconducting current at the interfaces between a superconductor and a ferromagnet with strong Rashba spin-orbit coupling. The appearance of such currents results in the induction of the stray magnetic field at the sample edges, local increase of the Cooper-pair density near the S/F interface, changes in the slope of the dependence $H_{c3}(T)$, and the substantial shift of the dependence of the magnetic field inside the ferromagnetic cylinder imbedded into the superconducting sample as a function of the external field.

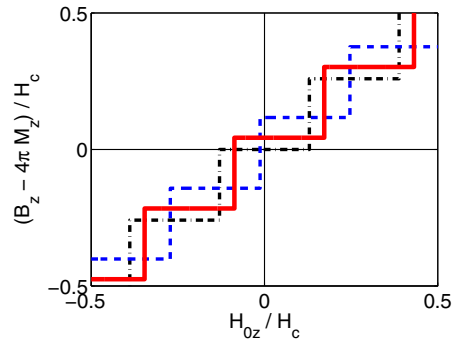

FIG. 3. The dependence of the magnetic field B_z inside the ferromagnetic cylinder as a function of the applied magnetic field H_{0z} (red curve). The dashed blue curve corresponds to the case when there is no spin orbit coupling in the system, the black dash dotted curve shows the dependence $B_z(H_{0z})$ for the case $M_z = 0$ and $\alpha_{so} = 0$. The radius of the F cylinder is $R = \lambda$, the parameter $\alpha_{so}h_z = 0.1\Phi_0/\pi$, $H_c = \Phi_0/\pi\lambda^2$, $M_z = 4.5H_c$.

Experimentally the spontaneous surface current should be revealed through the appearance of the magnetic field in the region where the S/F interface comes to the sample edge. In contrast with the stray magnetic field induced by the ferromagnet, the described spontaneous field emerges only below the superconducting transition temperature, which makes it easily distinguishable in magnetic measurements. The most appropriate techniques to observe the predicted effects are the scanning SQUID microscope with single electron spin sensitivity [32] or the local probe measurements of the faint magnetic field with the help of low-energy muon spin spectroscopy [33,34]. Note that the latter method offers extreme sensitivity to magnetic field of less than 0.1 G, with a depth resolved sensitivity of a few nanometers. From Eq. (3) one finds that with logarithmic accuracy the estimate for the spontaneous magnetic field at the S/F interface gives $\Delta H \sim p_{so}l_{so}H_{c1}(T)$, where $p_{so} = \varepsilon h_z/\gamma$ is the momentum characterizing the shift in the electron energy bands due to SOC, and $H_{c1}(T) = \Phi_0/(4\pi\lambda^2)$ is the lower critical field. Taking $l_{so} \sim 1-10$ nm, we obtain that the field ΔH can become of the order of H_{c1} or even exceed it. In the latter case, the spontaneous surface current should produce Abrikosov vortices near the S/F interface. Additionally, the emergence of the surface current can be observed in the H_{c3} measurements. At fixed temperature the difference δH_{c3} between the H_{c3} values for the parallel and the antiparallel orientations of the external field and the exchange field in the F layer is of the order of $\delta H_{c3}/H_{c3} \sim p_{so}l_{so}$. Thus, if $\varepsilon > 0$, then for $\mathbf{h}\uparrow\uparrow\mathbf{H_0}$ the SOC favors the emergence of the localized superconducting nuclei above the upper

critical field H_{c2}, while for $\mathbf{h}\uparrow\downarrow\mathbf{H_0}$ the formation of such nuclei can even become impossible (if $\varepsilon < 0$ the deviation of H_{c3} from H_{c3}^0 has the opposite sign). Finally, the spontaneous currents can be observed in cylinder geometry where for $p_{so}l_{so} \sim 1$ and $R \sim \lambda$ the shift of the steps on the dependence of the magnetic field inside the cylinder on H_{0z} due to SOC becomes of the order of the steps' width.

Note that the discovered phenomena should result in a variety of edge effects, such as renormalization of the surface barrier for the Abrikosov vortices, anisotropy of the depairing current in the regime of surface superconductivity, etc. Note also that these effects are not specific for S/F interfaces with SOC, but should also be relevant for a wide class of interfaces between superconductors and materials with spin polarization and broken inversion symmetry, such as topological insulators or other types of quantum spin-Hall systems.

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